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What Spatial Frequency Do We Use to Detect the Orientation of a Landolt C?

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We calculated the two-dimensional Fourier spectrum of a Landolt C. For Landolt Cs of orthogonal orientation, the main differences in the amplitude spectrum were found at a low frequency such that 1.3 periods were equal to the size of the Landolt C, rather than at the high frequency corresponding to the size of the gap, i.e., such that 2.5 periods were equal to the size of the Landolt C.
We compared visual acuity assessments obtained with Landolt C optotypes and the cut-off of the contrast sensitivity function measured with sinusoidal gratings. We found that the frequency corresponding to the size of the gap is twice the latter frequency. We suggest that, in fact, this lower frequency can be used to determine the position of the gap. © 1997 Elsevier Science Ltd.

Acuity Landolt C Optotype Spatial frequency Fourier analysis

INTRODUCTION

Visual acuity is usually defined as the finest spatial detail that the visual system can resolve. When letter optotypes are used the relevant detail is taken to be the stroke width, but letter acuity depends on the complexity of the individual letter used and probably too on the identity of the particular surrounding letters. In the last century Snellen and Landolt proposed the idea of testing visual acuity by using always the same stimulus in four orientations, thus avoiding the differences in resolution that depend on letter complexity.

Following a series of papers by Campbell, Blakemore and Robson (Campbell & Robson, 1968; Blakemore & Campbell, 1969), spatial frequency analysis became the preferred method for studying visual resolution. New acuity charts were developed composed of sinusoidal gratings or Gabor patches. Both the new charts and the Landolt C or Snellen E charts are valuable in the differential diagnosis of ophthalmological diseases (McGray *et al.*, 1995). However, comparisons of visual acuity assessed by different optotypes are not very common. Riggs (1965), for example, reported data obtained by different authors on measurements of visual acuity using Landolt C stimuli and rectangular gratings. The size of the gap of a Landolt C varied from 22 to 30 arc.min while "...the minimum width of stripe for grating resolution is in the neighbourhood of 1 minute of arc at moderately high levels" (p. 326) and varied from 35 to 64 arc.min as was reported in different studies. In another study, high spatial components of both grating and a Landolt C were gradually removed using the ground glass placed at the different distances from the stimulus plane and the probability of correct judgement of the grating/gap orientation was measured (Oda & Nakano, 1992). For gratings fall-off was obtained at the critical spatial frequency of 1/(gratings width ×2). The critical spatial frequency for Landolt C was twice that of the grating.

In addition, the repeated measurements of visual acuity showed that "...up to 13% of subjects displayed discrepancies of two lines or more on repeated testing" (McGray *et al.*, 1995). One possible explanation of these discrepancies may be that observers can learn to use different cues to detect the orientation, for example, of a Landolt C.

We encountered this question while studying the crowding effect using a Landolt C as a target (Bondarko & Danilova, 1995). We found that our observers were able to discriminate targets as small as 2.25–2.7 arc.min in diameter. The corresponding sizes of the gaps were 0.45–0.54 arc.min. In spatial frequency terms the size of the gap in these cases is equivalent to a frequency of 66.7–55.6 c/deg. However, this frequency is beyond these subjects' resolution limit. For example, we earlier found that the highest spatial frequency that one of our subjects could resolve is about 30 c/deg when tested using sinusoidal gratings. Higher spatial frequencies could be perceived by this subject only as Moiré patterns. At the same time the smallest diameter of a Landolt C that this subject could recognise was 2.25 arc.min. This fact led us to look for different cues that could be used by subjects when their task is to detect the orientation of a Landolt C.

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METHOD

We hypothesised that discrepancies between the data obtained with sinusoidal gratings and with Landolt Cs could be explained by considering the Fourier spectrum of the latter. We therefore calculated the two-dimensional amplitude spectrum of a single Landolt C.

We used a standard Landolt C, such that its strokewidth was equal to 1/5 of its outer diameter. The size of the gap was also equal to 1/5 of the diameter. The insert in Fig. 1(a) shows an example of the letter used. The orientation of the gap was one of the four possibilities: top, bottom, left, right.

The image of the Landolt C was described analytically as the difference between a ring and a rectangle. We did not use a standard "Fast Fourier Transform", because we wanted to obtain an adequate number of points in the low frequency range. A special program was developed to calculate the two-dimensional amplitude Fourier spectrum.

The Fourier integral was calculated by means of the so-called rectangular formula. It leads to approximation of the integral as a sum of sine and cosine values. Such a sum tends to the pure value of the integral as the size of rectangles tends to zero. We employed such small size of the rectangles that values of Fourier spectrum varied in the third decimal digit only. The equally spaced frequency steps were chosen in U- and V-axes and they were equal to 1/6 the diameter of a Landolt C.

Our figures demonstrate the general view of the two-dimensional spectrum and its cross-sections along vertical and horizontal frequency axes. Thus, one axis represents the direction containing the gap [which corresponds to summation along the V-axis, while $U = 0$; see insert in Fig. 1(a)], the other one represents the direction without the gap [which corresponds to summation along the U-axis, while $V = 0$; see insert in Fig. 1(a)].

RESULTS

Figure 1(a) presents the amplitude spectrum calculated in the direction without the gap (open circles) and the amplitude spectrum which was taken in the direction containing the gap (filled circles). The X-axis represents the harmonic number, i.e., spatial frequency relative to the frequency whose period is equal to the outer diameter of the Landolt C (the period of the first harmonic is equal to the size of the Landolt C, the period of the second harmonic is twice smaller the size, etc.). The Y-axis represents the amplitude in arbitrary units in linear scale.

Figure 1(b) shows the difference between these two amplitudes. This curve clearly shows that the maximal differences in the spectrum lie at frequencies such that 1.15–1.30 periods are equal to the target diameter, i.e., the size of a Landolt C but not at the frequency corresponding to the size of the gap which is equal to 2.5 harmonics. The ratio of the former frequency to the latter frequency has a value of about 2.

Figure 1(c) presents the general view of the two-dimensional amplitude spectrum. This figure demonstrates the differences in two orthogonal orientations only, which justified our consideration of these two orientations.

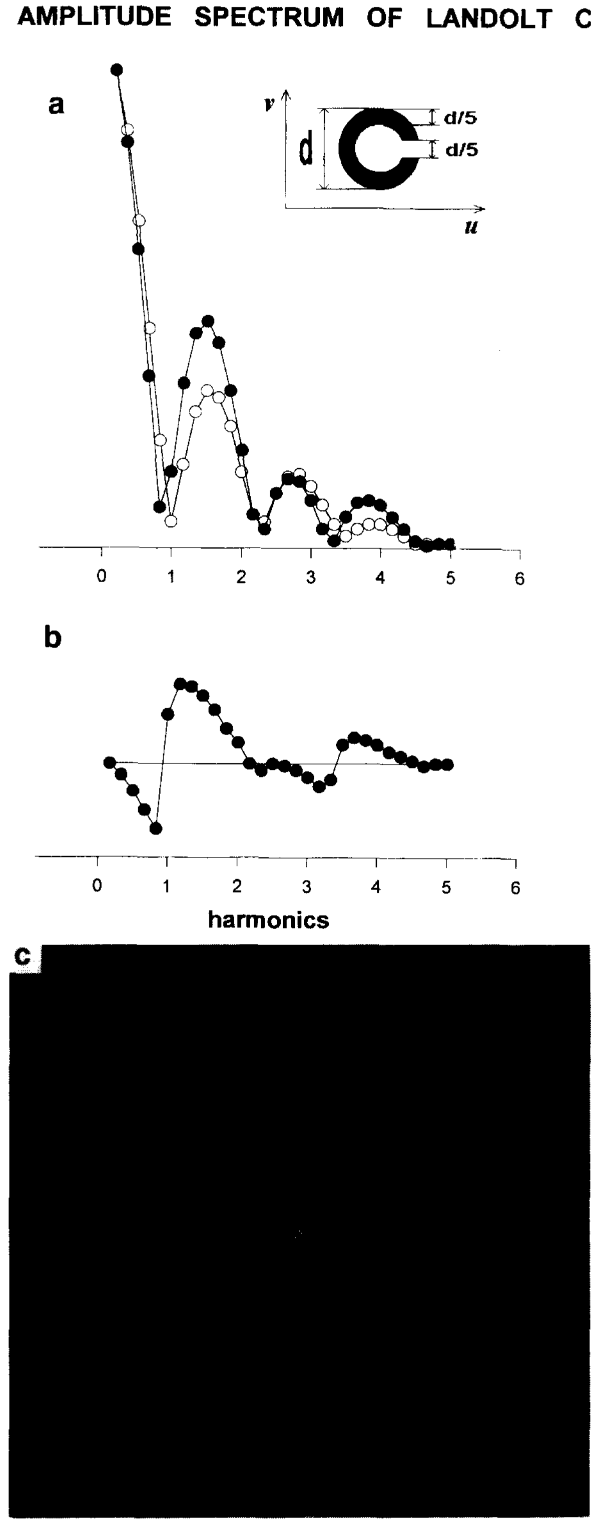

FIGURE 1. (a) The amplitude spectrum of the isolated Landolt C. The X-axis presents the harmonic number, the Y-axis presents the amplitude in arbitrary units in linear scale. Open circles show a spectrum calculated in the direction without the gap; filled circles show the direction with the gap. (b) The difference between two spectra calculated in different orientations. (c) The general view of the two-dimensional amplitude spectrum of the isolated Landolt C.

DISCUSSION

Thus, we obtained the spectral characteristic of a Landolt C and it appears that the spectra for different orientations have maximal differences at a frequency that is about two-fold lower than the frequency of the gap. We suggest that our trained observers specifically use this difference to detect the orientation of a Landolt C.

Our assumption may be indirectly confirmed by the subjective observations of naïve observers after the early, learning, phase of the above mentioned experiments by Bondarko & Danilova (1995). After the initial determination of adequate stimulus size (60–90% correct responses) and only 10 presentations of the isolated Landolt C all subjects stated that they rarely saw a gap. They described the stimulus as an asymmetrical spot having one "straight" edge and reported that they could detect the position of a gap only with a help of this asymmetry.

One can easily test this observation by looking at a Landolt C from a large distance. In this situation a Landolt C is similar to an asymmetric circle having one flat side, which signals the presence of a gap.

We have shown that vertically and horizontally oriented rings can be distinguished by the amplitude of Fourier components lower than the frequency that corresponds to the width of the gap. But what about left–right and top–down discriminations? These discriminations could be distinguished by phase. In fact, if we are to describe a Landolt C by function $F(x,y)$ considering the centre of the ring as the origin, then $F(-x,y)$ would represent changes of orientation from left to right or vice versa. The theory of the Fourier analysis states that in this case the phase characteristic also changes its sign at all frequencies (Korn & Korn, 1968). But when the amplitude of the corresponding frequency is small or negligible the discrimination based on this cue is impossible. The calculated spectra indeed show differences of amplitudes at the high frequencies [Fig. 1(b)]. But when we calculated the two-dimensional spectrum we did not take into account the optical modulation transfer function of the human eye and it is well known that the cut-off of this function is about 30 c/deg (Campbell & Gubish, 1966; Rovamo *et al.*, 1995). If we were to introduce the optical modulation transfer function, all differences beyond 30 c/deg would be negligible. The only significant differences will remain at lower frequencies.

When Landolt Cs are used in a clinical setting, it is possible that different people use different features to detect the position of a gap. Children or very cautious people may report the orientation only when a gap is clearly seen. However, for some people it is very possible that they can guess the position of a gap on the basis of the asymmetry of the spot. This may explain why some people can improve their visual acuity in successive testing: they can easily learn how to use other cues while not actually perceiving the gap more clearly.

The results of our analytical study of a Landolt C are in a good agreement with considerations of resolution capacity of a human eye, which in some cases does not result from clear separation of two objects. This question is discussed by Morgan (1990), who provided the example from Astronomy that "the two objects are not resolved in the exact sense of the Rayleigh criterion, but it is easy to deduce that two astronomical objects are involved rather than one from the shape of the light distribution" (p. 88).

Above all, our result may explain the factor two discrepancy between visual acuity assessments obtained with Landolt C optotypes and with sinusoidal gratings (Riggs, 1965; Oda & Nakano, 1992). The very similar result was obtained in 1755 by Tobias Mayer, who measured the acuity to detect a dot and rectangle grating. He also showed that the former acuity was twice the latter acuity (Mayer, 1755/1987). Subjects may use their highest available frequency to detect the orientation of a gap, but this frequency does not correspond to the size of the gap. And the lower frequency that they can use in this experimental situation is in good agreement with the assessments of visual acuity by sinusoidal gratings.

Having obtained these results we were led to ask whether an analogous result would be obtained for a Snellen E (Fig. 2). The amplitude spectra in this case do

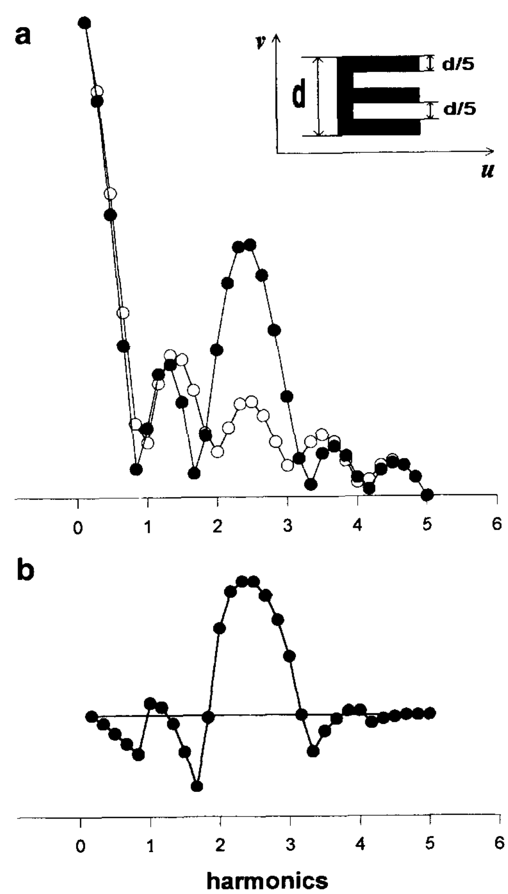

FIGURE 2. (a) The amplitude spectrum of a Snellen E. The X-axis presents the harmonic number, the Y-axis presents the amplitude in arbitrary units. Open circles show a spectrum calculated in the orientation orthogonal to the direction of the parallel bars; filled circles show the same orientation as the parallel bars. (b) The difference between two spectra calculated in different orientations.

exhibit significant differences at a frequency, the period of which corresponds to the size of the entire stimulus, but there are larger differences at a frequency corresponding to the size of the gaps [Fig. 2(b)]. This finding could be intuitively expected from the fact that a Snellen E incorporates a miniature grating.

We might conclude that Snellen E offers a better estimation of the highest spatial frequency that the visual system can resolve, and may be less susceptible to training effects than are measurements with Landolt Cs. However, even in the case of the Snellen E, at high luminance, the signal available to the subject at the gap frequency may be much attenuated by the optical MTF of the eye; and some subjects may then depend on the information available at the frequency corresponding to the size of the entire target.

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